

Recovery of p-modes in the combined 2004-2005 MOST[★] observations of Procyon

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ABSTRACT

Aims. Procyon A, a bright F5 IV-V Sun-like star, is justifiably regarded as a prime asteroseismological target. This star was repeatedly observed by MOST, a specialized microsatellite providing long-term, non-interrupted broadband photometry of bright targets. So far, the widely anticipated p modes eluded direct photometric detection, though numerous independent approaches hinted for the presence of signals in the $f \sim 0.5 - 1.5$ mHz range.

Methods. Implementation of an alternative approach in data processing, as well as combination of the MOST data from 2004 and 2005 (264 189 measurements in total) helps to reduce the instrumental noise affecting previous reductions, bringing the 3σ detection limit down to ~ 5.5 part-per-million in the $f = 0.8 - 1.2$ mHz range.

Results. This enables to cross-identify 16 p-mode frequencies (though not their degrees) which were previously detected via high-precision radial velocity measurements, and provides an estimate of the large spacing, $\delta\nu = 0.0540$ mHz at $f \sim 1$ mHz. The relatively low average amplitude of the detected modes, $a = 5.8 \pm 0.6$ ppm, closely matches the amplitudes inferred from the ground-based spectroscopy and upper limits projected from WIRE photometry. This also explains why such low-amplitude signals eluded the direct-detection approach which exclusively relied on the MOST 2004 (or 2005) data processed by a standard pipeline.

Key words. Stars: oscillations – Stars: individual: Procyon A – Techniques: photometric – Methods: data analysis

1. Introduction

Procyon A (F5 IV-V) has served as a prime target in many asteroseismological campaigns (see the reviews by Bedding & Kjeldsen, 2006,2007, and references therein). While high-precision measurements of radial velocities revealed the presence of variability caused by solar-like oscillations (Martić et al. 1999) and provided a preliminary identification of p-mode frequencies (Eggenberger et al. 2004; Martić et al. 2004; Leccia et al. 2007), the photometric studies met either limited success (Bruntt et al. 2005) or outright null-detection (Matthews et al. 2004; Guenther et al. 2007). The null-detection result was hotly debated ever since (Bedding et al. 2005; Régulo & Roca Cortés 2005). Attempting to resolve the controversy, we applied an alternative data-processing approach to the abundant photometric data acquired by MOST in 2004-2005.

2. Observations and data processing

The MOST satellite (Walker et al. 2003) is a 15-cm telescope acquiring high-precision, non-stop CCD photometric data on bright objects through a broad-band, 350-700 nm, optical filter. MOST observed Procyon A in 2004 (32-day non-stop observations, 231 524 0.9 s exposures: see the results discussed in Matthews et al. 2004), 2005 (taken over 17 contiguous days with

the general setup of the experiment following the 2004 campaign: Guenther et al. 2007) and 2007 (data are being processed: J. Matthews, 2007, priv. comm.). We took the publicly available raw data from 2004 and 2005 and processed them using an alternative algorithm (see the description in Aerts et al. 2006). While generally conforming to the approach of the standard processing pipeline applied to the 2004-2005 data, the alternative algorithm treats the highly variable stray light, the main source of instrumental noise, in a more flexible manner. In addition to the iterative subtraction of scattered light, the algorithm accounted for less substantial sources of instrumental noise, such as sensitivity drift caused by slow variations of the CCD temperature. The alternative approach resulted in a lower point-to-point scatter, $s = 440$ part-per-million (ppm), vs. $s = 500$ ppm (Matthews et al. 2004) (cf. the upper section of Fig 1). This should be compared to the projected level of the Poisson-dominated instrumental noise $s_{in} = 260$ ppm. The alternative approach also reduces the average (noise-dominated) amplitudes and scatter in the frequency spectrum: e.g., for $f = 1.05 - 1.25$ mHz one obtains $\bar{a}(f) = 2.8 \pm 1.7$ ppm in the older reduction vs. $\bar{a}(f) = 2.6 \pm 1.4$ for the new algorithm (Fig. 1). The modified approach, when efficiently combining the two available data streams (SDS1 and SDS2: see the definition in Aerts et al. 2006), proves to be even more effective with the 2005 data where the better planning of experiment allowed more straightforward suppression of the stray-light component, providing $s \approx 375$ ppm, which only moderately exceeds the expected level of $s_{in} = 250$ ppm. Predictably, the lower noise level brings down average amplitudes in the frequency domain: $\bar{a}(f) = 1.4 \pm 1.6$ ppm in the $f = 1.05 - 1.25$ mHz range, twice lower than in the data from 2004. On the other hand, the standard

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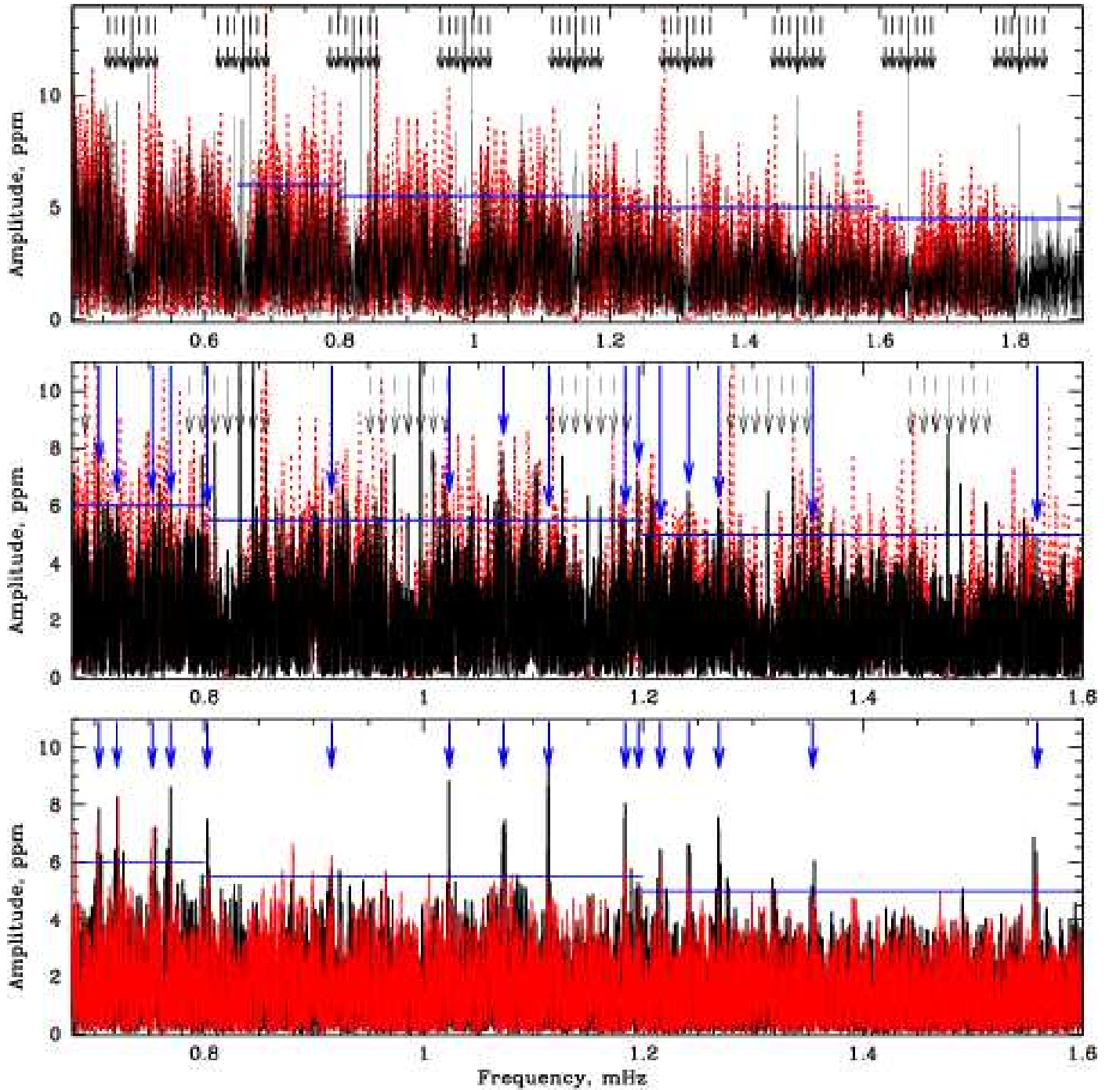


Fig. 1. The upper section shows the new spectrum (black lines) derived from the stand-alone 2004 data and the previously published (red lines) spectrum derived from the same data. The orbital harmonics and their $n \cdot 1/d$ sidelobes are marked by vertical solid-line and dashed-line arrows, respectively. Middle section: the Fourier amplitude spectrum calculated from the combined 2004-2005 data set processed with the alternative algorithm (black lines), compared to the published (Matthews et al. 2004: red lines) spectrum as a reference. Blue arrows mark the identified p-modes. Bottom section: an artificial spectrum calculated from the shuffled MOST 2004+2005 data with added stochastically-excited sinusoidal signals. Their frequencies are taken from Table 1. For simplicity, all the signals are assigned equal amplitudes $a=10$ ppm and lifetimes $L=7$ days (red lines), and $a=15$ ppm, $L=3$ days (black lines). Blue arrows mark the identified p-modes. In all sections the horizontal blue lines denote the 3σ detection limits.

approach (Guenther et al. 2007), relying uniquely on the SDS2 channel, provides a noise level comparable to the 2004 set.

During the processing of the 2004 data we kept the time-binning approach similar to the original scheme (Matthews et al. 2004); this provided a valuable point-to-point comparison between the two different approaches and retained

214 279 flux measurements. For the 2005 data we slightly changed the approach, by time-binning the SDS1 observations centered on the less frequent SDS2 measurements. On average, taking into account the higher rejection rates, the SDS1 data were ~ 5.5 times more abundant in the 2005 set. This time-binning approach resulted in 49 910 flux measurements.

3. Results

Our first step is to compare the frequency spectra calculated by the two data-processing algorithms. As anticipated, the alternative approach, while providing a frequency spectrum of an overall similar appearance, reduces the level of instrumental noise across the spectrum, save a few rare exceptions related to the harmonics of the orbital period (black arrows in Fig. 1).

The next step aims at an optimal combination of the data. A host of potential problems stems from: (a) the different durations of the 2004 and 2005 runs; (b) different planning of the experiments resulting in different levels of stray light; (c) presumably unstable nature of the signals. In the time domain we experimented with different lengths of segments derived from the original time series, varying them from 3 days to 2 weeks and producing a weighted combination of the frequency spectra derived from the segments. This allows us to see that the typical lifetime of signals does not exceed ~ 1 week. However, the segment-based approach comes at high price, raising in the region of interest, $f=0.5-2.0$ mHz, the detectability limits to an unacceptably high level, $a > 10$ ppm. Hence, we finally relied on the simplest and most straightforward approach, by combining the unweighted 2004 and 2005 data into a single set (Fig. 1). Obviously, this results in a further improvement of sensitivity: considering the 3-sigma level counted from the average amplitude of the noise-dominated signal, one is able to detect coherent oscillations with $a \geq 6.0$ ppm ($f=0.7-0.8$ mHz), $a \geq 5.5$ ppm ($f=0.8-1.2$ mHz), $a \geq 5.0$ ppm ($f=1.2-1.6$ mHz), $a \geq 4.5$ ppm ($f>1.6$ mHz), to be compared to $a \geq 7.0$ ppm ($f=0.5-2.0$ mHz: Matthews et al. 2004) and $a \geq 10-11$ ppm (Guenther et al. 2007). Beyond the overall improvement of sensitivity, such straightforward combination of the 2004 and 2005 data should substantially increase the chance of a positive detection which depends on the presumably short lifetimes of the coherent signals (p-modes) in Procyon A (Leccia et al. 2007) and the stochastic nature of the mode-excitation events (Kjeldsen & Bedding 1995).

As a first test of presence of any periodic variations, we derived a Fourier amplitude spectrum (AS) of the combined 2004+2005 data in the $f=0.5-2.0$ mHz domain specifically targeted in numerous observing campaigns. Then we calculated the number of peaks exceeding the 3σ detectability levels (see above). We also produced 10 samples via random shuffling of the real data and calculated the incidence of significant signals in the artificial ASs. We normalized the real data by the outcomes of simulations and show them in Fig. 2. There is a surplus of 3σ detections around $f \sim 0.8-1.4$ mHz, which closely matches the spread and location of the power excess determined from numerous independent spectroscopic runs (see Leccia et al. 2007 and references therein).

Further testing brings even more encouraging results. We select a prominent feature at $f=1.072$ mHz (Table 1 and Fig. 1) and search for a comb-like pattern (Kjeldsen et al. 1995) in the immediate vicinity of the peak. Scanning the adjacent region with $\delta f = 0.0001$ mHz steps, we find a maximum response at $f=1.0726$ mHz (Fig. 3), related to the large frequency separation of $\Delta f = 0.0540 \pm 0.0001$ mHz, in good agreement with $\Delta f = 0.0536 - 0.0559$ mHz consistently provided by all previous spectroscopic campaigns (Eggenberger et al. 2004; Martić et al. 2004; Leccia et al. 2007). The clear presence of a regularly-spaced signal in the MOST-2004 data was noted on multiple occasions: $\Delta f = 0.0545$ mHz (Régulo & Roca Cortés 2005), $\Delta f \sim 0.0548$ mHz (J. Matthews, priv. comm. 2005), also by the ref-

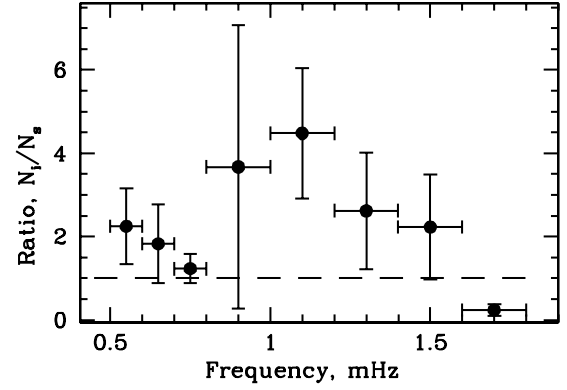


Fig. 2. The numbers (N_i) of significant (at 3σ level) peaks in the 2004+2005 AS normalized by the corresponding numbers (N_s) derived from artificial data sets. The vertical bars show the $\pm 1\sigma$ errors of the ratios. The horizontal dashed line provides a reference level of 1 (the case when all peaks are generated by noise).

eree of the article. Can the regular spacing of signals be caused by an unaccounted component of the stray light contributing to the $n * \nu_{orb}/3$ orbital harmonics with 0.0548 mHz separation? Apparently not, as the newly derived Δf is more than sufficiently distanced from the instrumental component. Moreover, we find only a very weak trace of the instrumental signal in the comb-generated response at $f=1.0726$ mHz and its complete lack at $f=1.6424$ mHz (Fig. 3: note that $f=1.6424$ mHz matches an orbital harmonic).

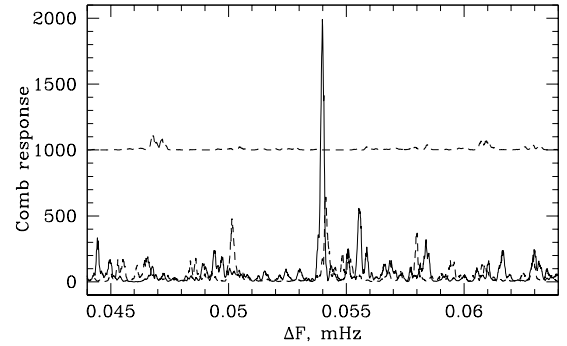


Fig. 3. The comb-response functions obtained for the central frequencies $f=1.0726$ mHz (full line), $f=0.9158$ mHz (dashed line) and $f=1.6424$ mHz (dashed line, offset for clarity). The tallest peak corresponds to a large separation $\Delta f = 0.0540 \pm 0.0001$ mHz, with the error derived from the FWHM of the peak.

The presence of a regular ‘comb’ of periodic signals around $f=1.072$ mHz prompted the final step of the analysis. We compiled a list of frequencies presumably related to p-modes (Eggenberger et al. 2004; Martić et al. 2004; Leccia et al. 2007) and searched for corresponding significant peaks in our 2004+2005 AS. We limited our search to the immediate surroundings of the published frequencies, i.e., to the $\pm \delta f \lesssim 0.002$ mHz intervals, where δf is an uncertainty related to frequency resolution in the AS derived on ~ 1 week-long runs. Note that a formal frequency resolution in the combined 2004+2005 AS reaches $3 * 10^{-5}$ mHz. We recorded the maxima which were very close to or above the corresponding 3σ levels for the given frequencies. Facing the rapidly rising level of instrumen-

Table 1. Detected p-modes

f [mHz]	2004+2005	Amplitude, 2004	a 2005	[ppm] 2004 ¹	References
0.7041	7.1	7.4	4.7	8.0	3
0.7206	6.0	6.0	5.6	—	2,4
0.7525	(5.6)	6.2	5.3	(6.6)	3
(0.7692)	6.2	6.3	4.0	7.5	3
0.8027	(5.0)	5.7	4.0	—	2,3
0.9158	6.1	6.6	5.3	9.0	2,4
1.0232	5.8	6.0	3.6	—	2,3,4
(1.0726)	6.2	9.2	8.1	7.6	3
1.1136	5.4	5.7	3.9	—	4
1.1837	5.6	6.5	2.1	—	2,3
1.1959	6.9	7.8	3.5	(6.2)	2,4
1.2158	5.0	5.4	4.2	—	3
1.2415	6.5	7.6	5.2	(5.2)	3
1.2692	5.9	6.1	3.3	(5.7)	2,3,4
1.3547	5.2	5.9	3.3	(6.0)	3
1.5590	4.9	4.9	4.4	—	2,4

¹ Matthews et al. 2004² Eggenberger et al. 2004³ Martić et al. 2004⁴ Leccia et al. 2007; raw data and fits.

tal+intrinsic (granulation?) noise, we disregarded all positive detections with frequencies below $f=0.7$ mHz. We also eliminated all positive detections (4 cases) which match high harmonics of the orbital period and their 1/d side lobes. We present the results in Table 1, where in parentheses we retain some prominent signals despite their relatively large deviations from the published frequencies. For a reference, we also provide the amplitudes of signals in the separate subsets from 2004 and 2005, even if they do not exceed detection limits. We compare our positive 2004+2005 detections with signals exceeding (or being reasonably close to) the detectability limits in the previously published MOST-2004 data (Matthews et al. 2004), finding $\sim 55\%$ of positive matches, both in frequency and amplitude. On average, one may expect 2.4 ± 1.2 (~ 20 in total) noise-generated signals exceeding the imposed 3σ threshold in an 0.1 mHz-wide bin placed in the region of interest, $f=0.7$ -1.6 mHz. Hence, the chance for an accidental match between a noise-generated peak and a pre-determined signal registered in the previous spectroscopic campaigns (Eggenberger et al. 2004; Martić et al. 2004) is $\leq 45\%$. I.e., at least 50% of the frequencies provided in Table 1 should be genuine. The 16 signals identified as p-modes, plus 20 noise-generated peaks do not account for all positive detections, 46 signals in the $f=0.7$ -1.6 mHz range. The origin of the 10 remaining peaks is unclear.

The average amplitude of the recovered signals, $a = 5.8 \pm 0.6$ ppm, closely matches the $a = 7.3 \pm 1.1$ ppm level inferred from the ground-based spectroscopy (Leccia et al. 2007) and $a = 8.5 \pm 2$ ppm upper limit from WIRE photometry (Bruntt et al. 2005). Such low-amplitude signals were inevitably swamped by instrumental noise in the previous reduction of the stand-alone data from 2004 and 2005. The unusually low level of the detected signals may be related to the anticipated short lifetime of the modes, 2.0 ± 0.4 d (Leccia et al. 2007). Indeed, one may re-shuffle the original 2004-2005 MOST data and add 16 sinusoidal signals with the frequencies matching the identified p-modes from Table 1. For simplicity, we assign to the signals the same amplitude a_{art} and lifetime L , let the phases of the signals vary randomly, then calculate the resulting ASa and show

them in Fig. 1. In both shown cases, $a_{art}=10$ ppm, $L=7$ days, and $a_{art}=15$ ppm, $L=3$ days, one may detect up to $\sim 80 - 90\%$ of the artificial signals. The $a_{art} = 10 \pm \text{ppm}$ case provides the average amplitude $\langle a_{art} \rangle = 5.0 \pm 0.8$ ppm, and $a_{art}=15$ ppm case results in $\langle a_{art} \rangle = 7.1 \pm 1.2$ ppm and a slightly better detection rate, thus proving the starting assumption about the short lifetime of the modes. On the other hand, the relative low signal/noise ratio of the data and, presumably, interaction of the stochastically excited modes affects the derived frequencies of artificial signals (f_{art}): $\langle |f_{obs} - f_{art}| \rangle \approx 9 * 10^{-5}$ mHz, to be compared to the formal frequency resolution $\delta f = 3 * 10^{-5}$ mHz in the combined 2004+2005 data..

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References

- Aerts, C., et al. 2006, ApJ, 642, 470
 Bedding, T.R., et al. 2005, A&A, 432, L43
 Bedding, T.R., & Kjeldsen, H. 2006, ESA Special Publication, 624, 25
 Bedding, T.R., & Kjeldsen, H. 2007, Comm. in Asteroseismology, in press (arXiv:0705.1376)
 Bruntt, H., et al. 2005, ApJ, 633, 440
 Guenther, D.B., et al. 2007, Comm. in Asteroseismology, 151, 5
 Eggenberger, P., et al. 2004, A&A, 422, 247
 Kjeldsen, H., & Bedding, T.R. 1995, A&A, 293, 87
 Kjeldsen, H., et al. 1995, AJ, 109, 1313
 Leccia, S., et al. 2007, A&A, 464, 1059
 Martić, M., et al. 1999, A&A, 351, 993
 Martić, M., et al. 2004, A&A, 418, 295
 Matthews, J.M., et al. 2004, Nature, 430, 51, Erratum: 430, 921
 Régulo, C., & Roca Cortés, T. 2005, A&A, 444, L5
 Walker, G., et al. 2003, PASP, 115, 1023